A RE-ENTRY VEHICLE REACTION CONTROL SYSTEM THERMO-FLUIDIC ANALYSIS APPROACH

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ABSTRACT

A general analysis methodological approach defined and implemented in the frame of a Reaction Control System (RCS) thermo-fluidic analysis campaign is presented. The developed approach is being refined to be adopted for the ESA IXV re-entry vehicle RCS design assessment activity.

The modelled RCS is basically a tubing network connecting a spherical elastomeric diaphragm propellant tank to the thruster units. Considering a common propellant such as hydrazine, thus liable of self-ignition above 75°C (167°F), the main objective is to give a comprehensive evaluation of the fuel behaviour through all the mission phases.

The variety of the analysis cases performed lets achieve the secondary objective of the study. The latter is to give an estimation of the maximum and minimum temperature reached by the items and devices constituting the RCS, such as valves, filters, etc.

To achieve such a result, a robust and reliable approach has been developed, to give both an acceptable run time and a precise solution focused to the temperature calculation especially into the network dead ends and stagnating branches. The environment the RCS copes with is a set of boundary conditions extrapolated from the System Level Thermal Mathematical Model (IOTMM) simulating the whole vehicle thermal behaviour.

As a result a set of three Sinda-Fluint models has been built to assess the worst operating conditions through which the hydrazine loop shall go during the whole mission duration. Moreover, the critical phase of purging operated by the pressurant discharge has been modelled, thus giving a clear description of the gas behaviour while flowing through the piping.

The results obtained through the analysis campaign are a key point of an RCS design assessment. Thanks to the adopted modelling techniques propellant temperature criticalities are easily spotted.

Further improvements from the items and devices thermal modelling standpoint are foreseen, for the actual configuration is mainly focused on the fluidic aspect.

INTRODUCTION

IXV is the acronym for the Intermediate eXperimental Vehicle (Figure 1), the ESA atmospheric re-entry demonstrator to be launched with Vega rocket from Kourou on 2014. The vehicle shall perform a suborbital flight and re-enter the atmosphere with a final splash down in the Pacific Ocean. Main goals of this demonstrator are to validate the thermal protection system versus re-entry thermal loads, aerodynamics, aerothermodynamics, Guidance Navigation Control (GNC) and descent and landing design together with the margin policy and tools adopted. The project had its Critical Design Review (CDR) on 2011 and is now in the manufacturing phase.

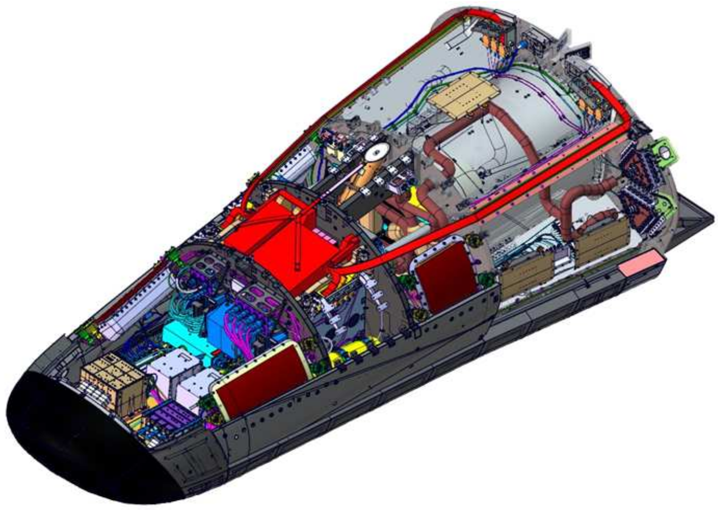

Figure 1. IXV Overview

The IXV Reaction Control System (RCS) consists mainly of a high pressure titanium storage tank for the hydrazine propellant (N_2H_4) divided by an elastomeric diaphragm from the nitrogen (N_2) pressurant (Figure 2). The propellant is connected via valves, filters and titanium hard lines to the external thrusters. In this case thermal/thermal hydraulic-analyses goals are to:

1. Assess the temperature reached by the propellant, highlighting possible criticalities as <u>self-ignition</u>, that occurs for temperatures above 75°C (167°F)

2. Check <u>main/max temperatures of the equipments</u> (valves, filters, etc.)

3. Provide inputs for thermal insulations (foam, MLI etc.) and Thermal Protection Systems (TPS) sizing

A complex thermal analysis campaign has been performed[1] working and interacting with different thermal tools and in particular:

- <u>ESATAN-TMS</u> for the IXV vehicle Integrated Overall Thermal Mathematical Model (IOTMM), required to perform the system level analysis

- Sinda-Fluint for the Thermal-Hydraulic Mathematical Model (THMM), to simulate priming, thruster firings, and N_2 purging

- NX Space Thermal for the external equipment detailed models for fine thermal mapping required also for thermo-elastic analysis

ANALISYS APPROACH

As far as THermal Mathematical Model (THMM) is concerned, Sinda-Fluint analysis tool was selected among others thermal hydraulic tools available for the following needs:

- Capability to model stagnant fluids conditions inside the tank

- Easy way to interface with IOTMM data

- Easy way to introduce fluid properties

- Code robustness and experience

- Good performance in terms of run time

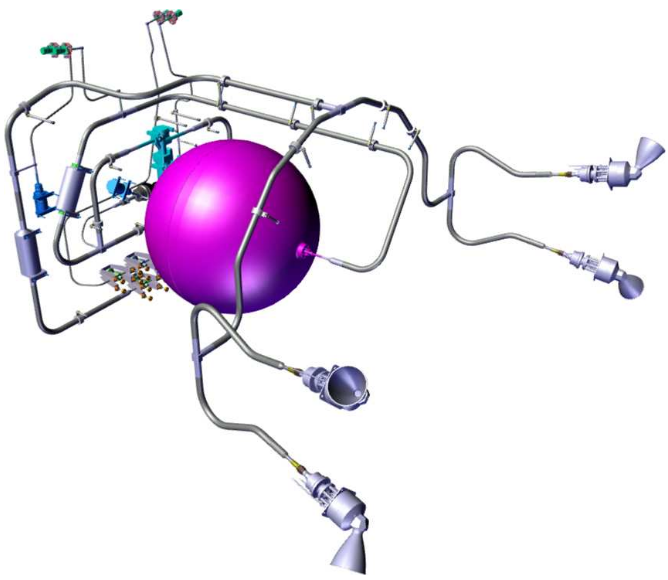

Figure 2. IXV's RCS

The purpose of the Sinda-Fluint model is to provide a comprehensive evaluation of the RCS behaviour for fluid (hydrazine) - routed inside a dedicated fluid loop - thermo-fluidic standpoint. The main objective is to assess the temperature reached by the propellant to highlight potential criticalities through the whole tubing equipment during the vehicle mission from priming to splash-down.

The secondary objective of the study is to give an estimation of the maximum and minimum temperature reached by the items and devices constituting the RCS (valves, filters, etc.).

The RCS is modelled as a standalone network coupled to the IOTMM. Output data of the latter TMM were used as a boundary environment for the RCS thermo-fluidic model.

The data set used as a source for the boundary environment was generated in the frame of the IXV System Thermal Control (TCS) analysis campaign (conducted from PDR level to CDR maturity) mainly focused on giving evidence of the thermal behaviour of the thrusters during re-entry when exposed to plasma / aero-thermal heat fluxes.

ESATAN TMS thermal network solver is the software mainly used for this purpose. It is the standard European thermal analysis tool used to support the design and verification of space thermal control systems.

MODELING THE RCS NETWORK

The modelled network is constituted by 148 fluidic nodes and 443 thermal nodes.
The model is then configured into three different setups, respectively devoted to each of the following objectives:

- *Configuration 1* – hydrazine and items maximum temperature check during orbital and re-entry phases
- *Configuration 2* – gas and hydrazine efflux during purging phase
- *Configuration 3* – hydrazine and items maximum temperature checking during descent phase

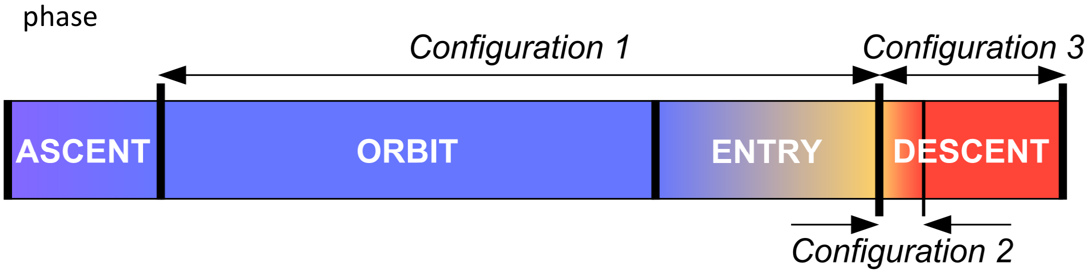

Figure 3. Mission timeline scheme versus model configurations implementation

Each configuration simulates a different part of the IXV mission, split into different phases (Figure 3), the last one being the worst for the heat wave dampened by the TPS reaches the vehicle interior during the descent period.
Into the first and third configurations the propellant stored into the tank is almost stagnating. A good approximation during orbit and entry phases, for the mass flow is set to the minimum assessed value (worst case), and a realistic assumption during the descent, when the thrusters are shut off. The pressurant is also considered as stagnating in both *Configuration 1* and *3*. In the latter case the pressurant is the residual part after the purging phase.

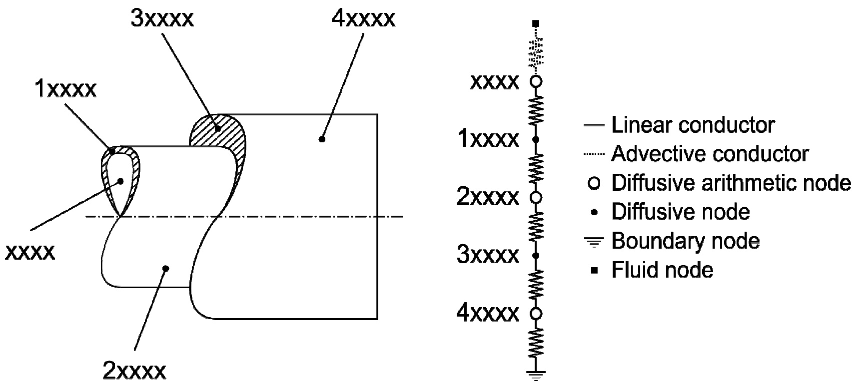

Figure 4. Tubing segment thermal nodal breakdown

Also into the second configuration the propellant is considered as stagnating while the stagnation condition is not set for the gas, for it is actually facing a rapid efflux from the tank. Each circuit branch has been modelled with a detail level suitable to the modelling needs. This means that the tubing is split into several segments, each one consisting of thermal and fluidic nodes radially chained together to form a network (Figure 4) representing the fluid, the tubing elements, and the insulation mitten wrapped around them (each segment consists of one or more radial subnets). A segment is longitudinally split into more than one subnet when one or more standoffs are linked to it. The subnets are then linked together by means of longitudinal conductors. The generated code is highly parameterized, allowing the user to make the model detail finer or coarser with ease and where needed. Geometrical changes (piping length and diameter, insulation thickness, elbows angles and curvature) are also easily doable.

Sinda-Fluint tie-conductors are able to connect fluidic and thermal nodes, taking into account the design parameters.

A custom tie has been set for both the tank internal volumes which are linked to the tank inner arithmetical thermal node. The contact surface is proportional to the volume occupied by the fluid, i.e.:

$$A_{FLUID \to TANK} = 4 \cdot \pi \cdot r^2 \frac{V_{FLUID}}{V_{TANK}} \qquad (1)$$

The tubing standoffs are modelled and link the relevant tubing segments to boundary nodes representing the internal IXV structure, the temperature trends of which are assessed by means of the IOTMM analysis.

The external arithmetic node wrapping each item is linked to an environment boundary node by means of an equivalent thermal conductivity simulating the convection occurring between the insulation material and the vehicle internal air, i.e.:

$$GL_{ENV} = H_{AIR} \cdot \pi \cdot d_{\text{INS, external}} \cdot l \qquad (2)$$

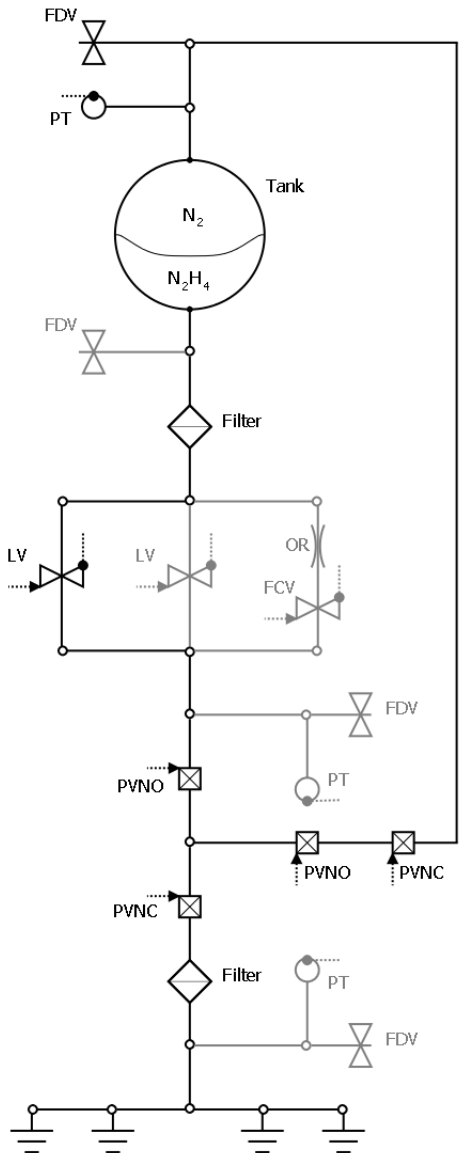

Figure 5. RCS full model breakdown (stagnating H_2N_2 branches are greyed out)

The particular case of the tank has been considered by using the spherical equation, i.e.:

$$GL_{ENV} = H_{AIR} \cdot 4 \cdot \pi \cdot r^2_{\mathrm{INS,external}} \tag{3}$$

For no radiative exchange has been considered, the H_{AIR} value is overestimated and set to 5W/m^2/K.

Pressure drops due to tubing roughness are automatically calculated by Sinda-Fluint once the relevant roughness value is provided.
Pressure drops due to the presence of valves, filters, restrictors, and other components are based on experimental data.
Elbows pressure drop coefficients are calculated with semi-empiric correlations by I.E. Idelchik[2].
Tees pressure drop coefficients are instead calculated with semi-empiric correlations by I.E. Idelchik[2] integrated into Sinda-Fluint subroutines, nested into a custom subroutine able to apply them coherently with the flux direction.

MODELING ISSUES AND ASSUMPTIONS

To model a thermofluidic network capable of high efflux rates occurring at high frequencies is quite a challenging task. For the scope of the analysis campaign is a thermofluidic evaluation, thus not focused to the propulsion matter, the modelling approach is consistent with the thermofluidic behaviour of the system but cannot be considered suitable for a functional verification.
Some assumptions have been made to obtain:

- Model stability and robustness (to face convergence issues in high pressure solutions and circuit dead ends)
- Fast calculation
- Optimal accuracy from the thermal standpoint

To achieve these key points the following assumptions have been implemented:

- The analysis start point is set to the beginning of the orbital phase, for the ascent phase is a cold phase and no heating is foreseen at fluid level
- The model is provided with a worst-case mass flow rate at thrust devices level, thus not

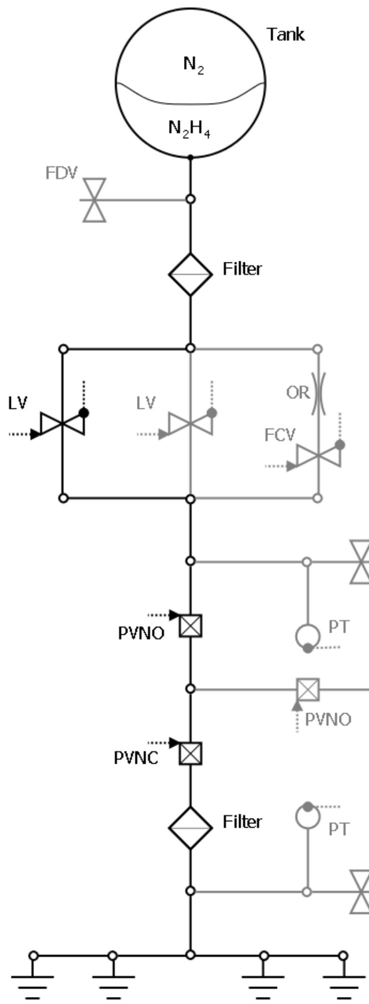

Figure 6. *Configuration 1* model breakdown (stagnating H_2N_2 branches are greyed out)

simulating the work logic of the thruster, avoiding numerical issues due to fast transient shifts (strong variations in flow rate due to thrusters' shooting)

- Liquid is considered "slightly compressible"; despite the fact that hydrazine could be considered as an uncompressible liquid in real world, it is necessary to set a liquid compliance to cope with convergence issues in high pressure working states
- Radiative exchange is neglected while equivalent advective conductance is fixed to a largely conservative value
- The whole closed hydrazine branch but the propellant tank compartment is missing in the code of purging phase model (*Configuration 2*, Figure 7); for this part of the network is already been evaluated by *Configuration 1* and *3* there is no reason to maintain it active during the purging analysis

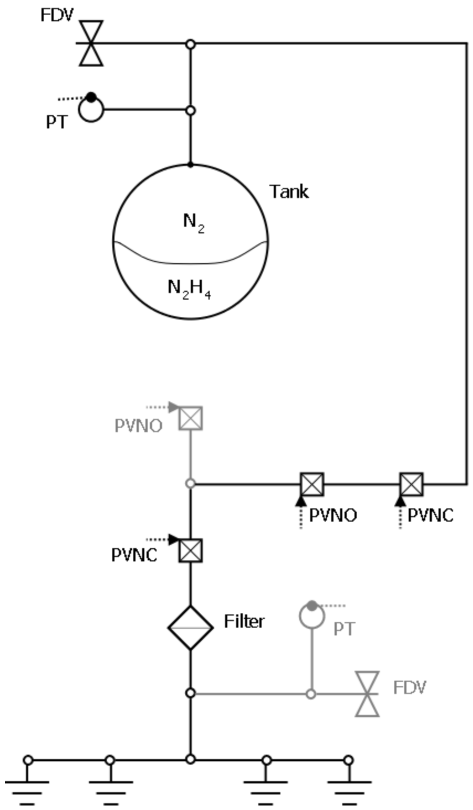

Figure 7. *Configuration 2* model breakdown (stagnating H_2N_2 branches are greyed out)

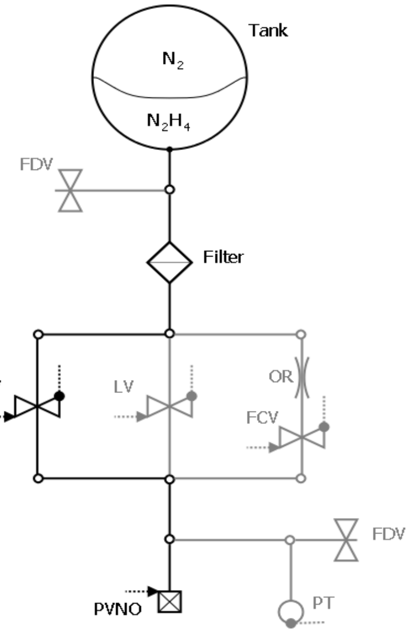

Figure 8. *Configuration 3* model breakdown (stagnating H_2N_2 branches are greyed out)

- The whole closed nitrogen branch but the pressurant tank compartment is missing in the code of *Configuration 1* and *3* (Figure 6 and Figure 8). For this part of the network is barely relevant during the purging analysis

- The *Configuration 3* barely models the non-purged branches (Figure 8), for they are the unique critical branches left after the purging phase

ANALYSIS, RESULTS, AND THEIR APPLICATION

For the whole IXV design is devoted to cope with the re-entry heating effects, a unique design case was selected and performed to represent the worst-case hot condition from the thermal standpoint (extreme environmental temperature, minimum flow rate).

The majority of the lumps reports a temperature level well below the limits (Figure 9). Hydrazine stagnating in non-operative conditions during the descent phase exceeds both the maximum allowed non-operative temperature (70°C) and the qualification temperature (60°C).

This criticality was not highlighted by analyses formerly performed with other tools that did not consider fluid phenomena, thus confirming the importance of a fine grain modelling approach in the frame of a critical system evaluation.

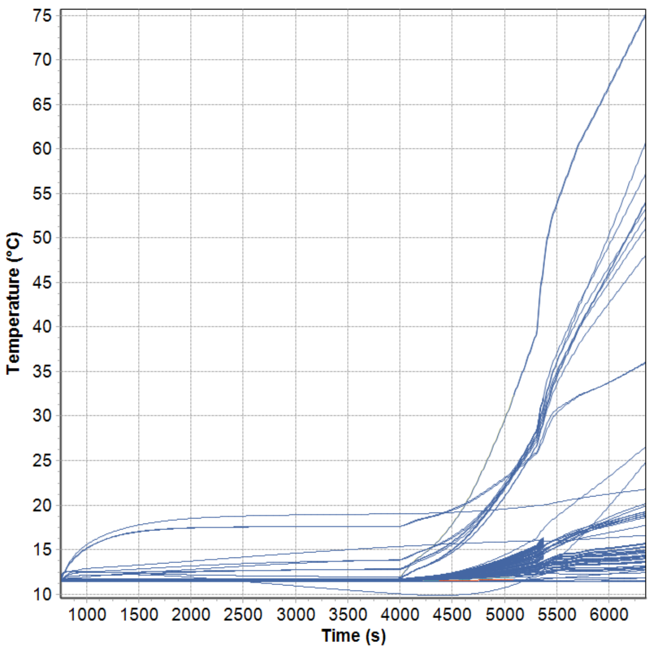

Figure 9. Lumps temperature trends

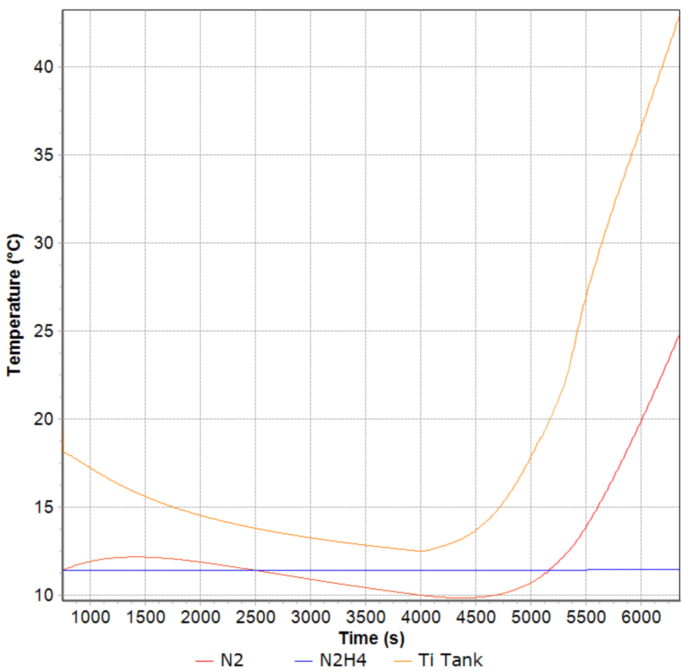

Figure 10. Tank and stored fluids temperature trends

The parametrization upon which the modelling is based permitted to focus on the solution of each issue by acting on an item's configuration as far as a proper design was achieved. The requirement violation was assessed for hydrazine contained in dead branches (e.g. those used for fluid fill). Design solutions to the highlighted problems were identified, i.e. by further decreasing the couplings with structure and mitigating the surrounding hot environment effects.

On the contrary, the thermal design proposed for the propellant/pressurant fluids stored in the titanium tank allows having

predictions compliant with design requirements as shown in Figure 10.
The hydrazine temperature in transient mode during the mission was injected into the IOTMM as an input to the thrusters thermal analysis. Nevertheless, there was no alternate option to follow because of the impossibility to merge different models into a unique one, for IOTMM was unable to withstand the calculation requirements (i.e. inability to treat stagnant fluids).
The purging analysis output highlighted no criticalities about temperature experienced by the components during the rapid expansion due to the nitrogen discharge. Moreover, for the discharge shall be shut off before the complete emptying of the pressurant half of the vessel, a prediction of the time needed to achieve a complete hydrazine expulsion was a key requirement. The latter was easily fulfilled by the model as shown in Figure 11.

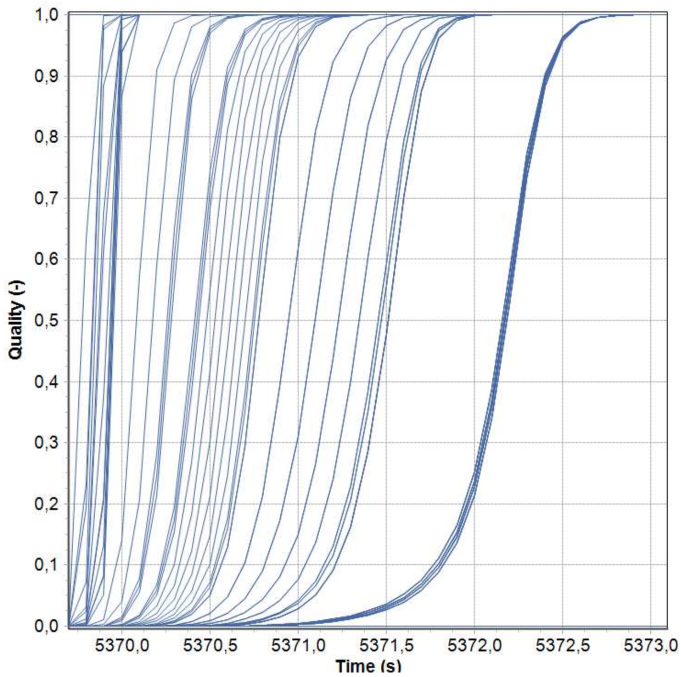

Figure 11. Fluid quality versus purging time trends (1 = full N_2, 0 = full N_2H_2). Left to right curves represent tank to discharge valves lumps

FURTHER IMPROVEMENTS

Proven flexibility of the developed modelling approach is confirmed by support analyses later performed to provide input feeding pressure and mass flow rates to GNC thruster control look-up tables, by simulating single thrusters shots at specific instants during both orbit and entry phases.
This activity improved the maturity level of the model. The latter, unable to withstand impulsive flow rates in early development stages, demonstrated a robustness which represents a key point for ongoing improvements foreseeing a more realistic thruster working logic.

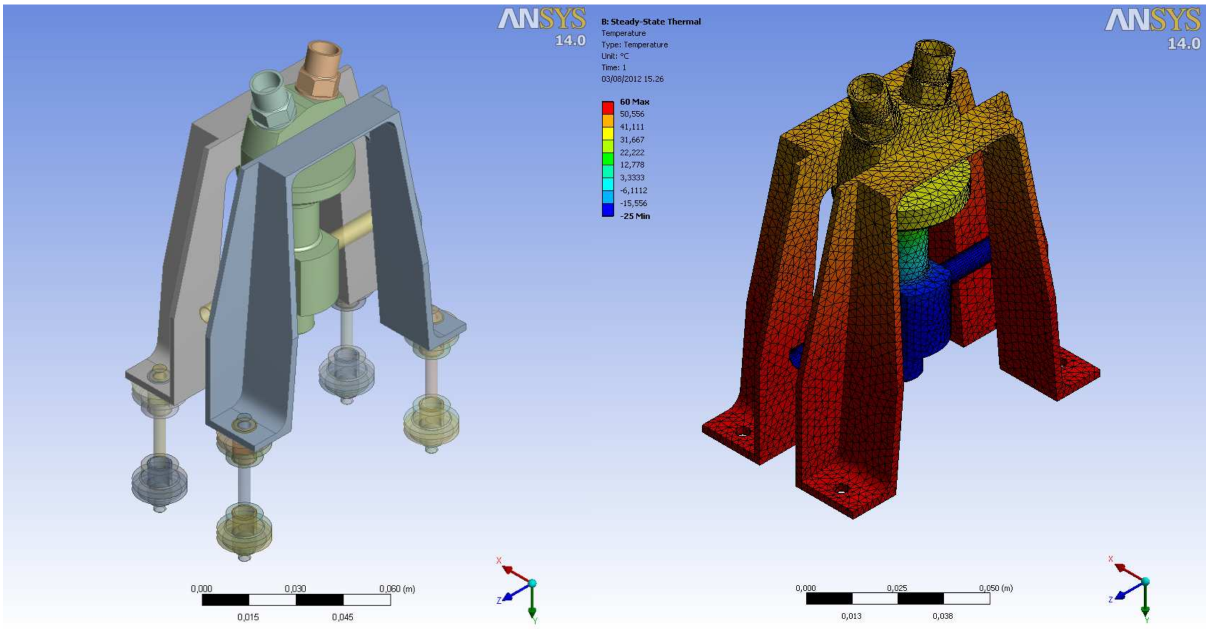

Figure 12. Pyro valve standoff-to-fluid thermal conductor assessment preliminary results in ANSYS Workbench 14.0

From the thermal standpoint, ongoing activities will provide the model with highly representative thermal couplings connecting the RCS to the internal vehicle structure. FEM tools are being used to assess thermal conductors through complex geometry items (e.g. Figure 12), such as brackets, valves, filters, etc…, in lieu of the current ones based on simplified geometrical models.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

FCV	Fluid Control Valve
FDV	Fill (and) Drain Valve
FEM	Finite Element Method
GNC	Guidance & Navigation Control
ID	Identifier
IXV	Intermediate eXperimental Vehicle
LV	Latch Valve
NC	Normally Closed
NO	Normally Opened
OR	Orifice
PT	Pressure Transducer
PV	Pyro Valve

R.D. Reference Document

RCS Reaction Control System

TCS Thermal Control System

TMM Thermal Mathematical Model

REFERENCES

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2. Handbook of Hydraulic Resistance, Idelchik, I.E.